Grid-Forming Control Suitable for Large Power Transmission System Applications

Taoufik Qoria, Xavier Guillaud, *Member, IEEE*,

Abstract—The inner cascaded structure-based grid-forming control is a typical solution used to impose an AC voltage magnitude across the output filters of the power inverters. Yet, because of the limited inverter’s bandwidth resulting from the low-switching frequencies in transmission systems, the interaction (i.e., coupling) between control loops is highly likely making the understanding of the system behavior complex and its simplification unaffordable and may also lead to instabilities. The novelty of this paper consists in proposing a simple open-loop direct voltage control to reduce the number of the inner control regulators, and thereby guaranteeing a decoupling between the inner and outer control layers as well as increasing the system stability margin. This statement is well supported with a small-signal analysis and progressive order model reduction of the system. The overall concept is validated in a 10-bus grid case while comparing the EMT and Phasor-based simulations. The practical feasibility of the control itself is experimentally proved with different test cases.

Index Terms—Grid-forming VSC, AC voltage control, Order Model Reduction, Electromagnetic Transient Simulations, Phasor Simulations.

I. INTRODUCTION

IN power transmission systems with high penetration rate of inverters-interfaced generation, the way to control the power inverters should be improved or radically changed in order to overcome the limitations of the conventional grid-following control [1], [2]. In other words, the way to control power inverters has to be changed from “following the grid” to “supporting the grid”. In this context, the grid-forming capability seems to be a suitable alternative for this aim thanks to the potential it brings to the power inverter e.g., voltage source behavior, inherent inertia emulation and the ability to operate in both grid-connected and standalone mode. Several grid-forming variants have been proposed in the literature. These solutions adopt more or less the idea of mimicking the swing equation of a synchronous machine (SM) [3]–[8] to generate the control angle. Regarding the AC voltage magnitude, it is managed by a lower control level (i.e., inner control). One common solution to control the AC voltage magnitude is the cascaded control structure [9]–[11]. This solution is favored for industrial applications because of the simplicity of its implementation and its ability to generate a current reference that serves to protect the inverter against faults. Yet, because of the limited inverter’s bandwidth resulting from the low-switching frequencies in transmission systems, the tuning

of the controllers based on this structure is still a challenge making the system stability in a stiff grid condition and the interaction between control layers a major problem [12]. Many studies reported the instability issue of grid-forming VSCs especially in stiff grid conditions, where the stability impact factors were analyzed by the state-space model [13] or the impedance model [14], including the control parameters, the operating point and the grid impedance. Recently, new tuning methods to face this problem have been proposed [9], [10], [15]. However, the explicit control interaction mechanism between control loops leading to this instability was overlooked and few researches broach this research area [16], [17]. In [17], the authors have clearly demonstrated via frequency analysis that the sub-synchronous resonances can be induced in stiff grids, owing to the interaction of inner voltage, current controls and the outer power control loop. In [16], the authors have highlighted the interaction between inner control and outer control loops through a comparison between Phasor and EMT models, in which the voltage and current control parameters play a crucial role. In [11], participation factors have been used to show that the instability of a grid-forming inverter in stiff grid conditions is a consequence of interaction between the current loop and voltage loop. In these prior researches, the control interaction problem is reported through different analysis, however, no solutions have been proposed to guarantee a decoupling between control layers.

The interaction between control loops is not only affecting the system stability, but also making the understanding of system behavior and its simplification for large system’ studies unaffordable, which imposes on system operators in the future to use EMT simulations instead of Phasor ones. This affirmation has been claimed in [20], where the authors conclude the non-effectiveness of the phasor approximation method for model reduction in case of high penetration rate of a grid-forming-based power electronics devices. However, it is important to mention that authors in [20] have drawn this conclusion using the cascaded inner control structure in the overall studied power system.

Based on this prior state of the art, the authors of this paper believe that reducing the number of the controllers may be the right option to tackle the problem of interaction and stability. In this context, the direct AC voltage control structure appears an appropriate solution. This concept has already been proposed in [21], [22]. These solutions consist of a mono-voltage control loop based on an integrator controller to regulate the AC voltage in normal operation. However, in case of faults, the control still need to switch from direct voltage to direct current control, which results in a voltage latch-up and requires a re-tuning of the integrator gain to guarantee a

This work is supported by ELIA Transmission System Operator.

Taoufik Qoria is with Maschinenfabrik Reinhausen, MV-Power Electronics departement EAP, 93059; Regensburg, Germany (t.qoria@reinhausen.com)

Xavier Guillaud is with L2EP, Univ. Lille, Arts et Metiers Institute of Technology, Centrale Lille, Yncrea Hauts-de-France, ULR 2697 Laboratoire d’Electrotechnique et d’Electronique de Puissance, F-59000 Lille, France

Fig. 1: General configuration of the Current-control free grid-forming VSC

stable switching back to the voltage control mode. From an other side, to the best of our knowledge, no research highlights the benefits of the direct AC voltage on large power systems in terms of simplicity and equivalence with the Phasor models. This paper looks to fill this gap by proposing the following contributions:

- Recommending extra control functions along this paper to enhance the system operation.
- Proposing a simple open-loop direct AC voltage control with a small-signal stability analysis.
- Assessing the decoupling between different control layers through model order reduction.
- Confirming the effectiveness of RMS simulations compared to EMT ones in a 10-bus grid-case.

The practical feasibility of the control itself is experimentally proved under normal and abnormal conditions. The remaining of this paper is organized as follows. In section II, the grid-forming structure is presented and explained. In section III, the direct AC voltage control is developed and its decoupling with outer controllers is proved and discussed. Section IV validates the proposed control. Finally, section V concludes the paper.

II. GRID-FORMING-BASD VOLTAGE SOURCE INVERTER

The power model and the control structure of the grid-forming VSC are presented in Fig. 1. The VSC is supplied by a perfect DC bus u_{dc} and connected to the AC grid through an LC filter and an equivalent transformer impedance. The grid side is modelled by an equivalent Thevenin voltage v_e in series with equivalent R_g, L_g . With regard to the control side, the outer control loop consists of the active and reactive power controllers, which generate the voltage angle θ_m and magnitude reference e_{gdq}^* with respect to the predefined set-points and measured power imbalance. The reference voltage vector signal is sent to the voltage regulator, and then to the modulation stage. Each control function illustrated in Fig. 1 is further explained in the following sections.

A. Dynamic equations of the system

The electrical system consists of an input LC filter (L_f, C_f) and a transformer equivalent impedance L_c to model the iron losses. It is modeled in the synchronous rotating frame (SRF) defined by the inverter angle θ_m . The SRF dynamic equations of the system in s-domain are formulated as follows:

$$s i_{sd} = \frac{\omega_b}{L_f} (v_{md} - e_{gd}) - \left(\frac{R_f}{L_f} i_{sd} + \omega_m i_{sq} \right) \omega_b \quad (1)$$

$$s i_{sq} = \frac{\omega_b}{L_f} (v_{mq} - e_{gq}) - \left(\frac{R_f}{L_f} i_{sq} - \omega_m i_{sd} \right) \omega_b \quad (2)$$

$$s e_{gd} = \frac{\omega_b}{C_f} (i_{sd} - i_{gd}) - \omega_b \omega_m e_{gq} \quad (3)$$

$$s e_{gq} = \frac{\omega_b}{C_f} (i_{sq} - i_{gq}) + \omega_b \omega_m e_{gd} \quad (4)$$

$$s i_{gd} = \frac{\omega_b}{L_c} (e_{gd} - v_{gd}) - \left(\frac{R_c}{L_c} i_{gd} + \omega_m i_{gq} \right) \omega_b \quad (5)$$

$$s i_{gq} = \frac{\omega_b}{L_c} (e_{gq} - v_{gq}) - \left(\frac{R_c}{L_c} i_{gq} - \omega_m i_{gd} \right) \omega_b \quad (6)$$

The active and reactive power formulas in SRF are given by:

$$P = e_{gd} i_{gd} + e_{gq} i_{gq} \quad (7)$$

$$Q = -e_{gd} i_{gq} + e_{gq} i_{gd} \quad (8)$$

The system state variables are the VSC output current i_s flowing through the filter L_f , the AC voltage e_g across the capacitor filter C_f and the grid current i_g flowing through the transformer impedance L_c , respectively. The modulated and the grid voltages are denoted by v_m and v_g . ω_b represents the system base frequency and ω_m is the inverter frequency in per-unit.

B. Power Control

In this paper, the outer active power controller is based on the PLL-free PI-controller [8]:

$$\omega_m = \frac{1}{2Hs} (\gamma P^* - P) - k_p P \quad (9)$$

$$\theta_m = \omega_m \omega_b / s \quad (10)$$

with H , k_p and P^* denote the inertia constant, the damping factor and the active power setpoint, respectively. θ_m denotes the time-domain angle. γ is an adaptive gain that aids the grid-forming to stably resynchronize after large disturbances [25]. It is determined by the virtual impedance control when the current exceeds its rated value (see subsection D).

In addition to the ability of the PI-controller to provide an inertial response, it takes the advantage of guaranteeing a decoupling between the active power regulation and the frequency support function exactly as a VSM [8], but without a need to a dedicated PLL, which makes the power control much simpler.

The frequency support block is a classical frequency droop control:

$$P^* = \frac{1}{R} (\omega^* - \omega_m) \quad (11)$$

R denotes the droop gain.

Regarding the reactive power outer controller, it is based on the conventional reactive droop function:

$$Q^* - Q \left(\frac{1}{1 + T_Q s} \right) = \frac{1}{n_q} (e_{gd}^* - E_g^*) \quad (12)$$

with Q^* , E_g^* , n_q and T_Q denote the reactive power reference setpoint, the voltage setpoint, the reactive droop gain and the reactive power time constant, respectively.

C. Transient Virtual Resistor (TVR)

During transients, maintaining a constant voltage would induce synchronous oscillations due to the undamped line dynamics ($X \gg R$) [12], [21], especially in case of stiff grid conditions. These oscillations may result in unstable system operation in case of fast active power dynamics ($T_R^{5\%} \leq 100\text{ms}$) [2]. To avoid the consequent instability, a TVR should be adopted in the control to damp the grid current dynamics and thereby, ensures a frequency decoupling between the grid current dynamics and the power control dynamics. The TVR expression is given in the following line:

$$\delta v_{R_{dq}} = R_v \left(\frac{s}{\omega_f + s} \right) i_{gdq} \quad (13)$$

R_v is the virtual resistor. ω_f is the cut-off frequency of the high-pass filter.

D. Virtual impedance for current limitation (VI)

The VI principle consists in increasing the output impedance during the overcurrent period in order to reduce the inverter voltage magnitude and accordingly limiting the output current. This solution has been used in this paper because of the absence of a current regulation loop in the proposed control, and also because of its ability to improve the transient stability

of the system.

As illustrated in Fig. 2, the VI operation principle is divided into two main phases:

- Overcurrent detection and VI calculation (activates only when the current exceeds its nominal value $I_n=1$ p.u).
- AC voltage drop calculation.

The expressions of X_{VI} , and R_{VI} are given in (14) and (15).

$$X_{VI} = \begin{cases} k_{p_{R_{VI}}} \delta I \sigma_{X/R} & \text{IF } \delta I > 0 \\ 0 & \text{IF } \delta I \leq 0 \end{cases} \quad (14)$$

$$R_{VI} = X_{VI} \sigma_{X/R}^{-1} \quad (15)$$

where $\delta I = I_s - I_n$. $k_{p_{R_{VI}}}$ and $\sigma_{X/R}$ are defined respectively as the virtual impedance proportional gain and the virtual impedance ratio. The parameter $k_{p_{R_{VI}}}$ is tuned to limit the current magnitude to a suitable level I_{max} in steady state.

When the virtual impedance is activated, the new AC voltage references are given by (16) and (17):

$$e_{gd}^* = e_{gd}^* - \delta e_{g_{VI}d} \quad (16)$$

$$e_{gq}^* = -\delta e_{g_{VI}q} \quad (17)$$

with:

$$\delta e_{g_{VI}d} = (R_{VI} + K_D) i_{sd} - X_{VI} i_{sq} \quad (18)$$

$$\delta e_{g_{VI}q} = (R_{VI} + K_D) i_{sq} + X_{VI} i_{sd} \quad (19)$$

E. Post-fault Re-synchronization algorithm

In case of large disturbances, the resulting power mismatch during faults may lead to a loss of synchronism. To face this issue, an adaptive gain γ given in (20) is implemented in the power control loop (see (9)) in order to adapt the active power reference with respect to the voltage generated by the VI. If the current does not reach its maximum allowable value I_{max} , the gain γ is equal to 1. While, when a fault occurs and the current is above its rated value, the factor γ is modified with respect to the VI voltage leading a decrease of the power reference, and thereby to a larger angle stability margin. More information on this gain are found in [25].

$$\gamma = \sqrt{(1 - \delta e_{gd})^2 + \delta e_{gq}^2} \quad (20)$$

Fig. 2: VI structure

III. DIRECT AC VOLTAGE CONTROL & ORDER MODEL REDUCTION

A. Principle of the Direct AC Voltage Control

The aim of the inner control is to set a specified voltage magnitude across the capacitor C_f . To achieve this objective, the modulated AC voltage reference $v_{m_{dq}}^*$ is generated from the voltage setpoint $e_{g_{dq}}^*$ and the inverse of the quasi-stationary model of the filter R_f, L_f :

$$v_{m_d}^* = e_{g_d}^* + R_f i_d - L_f \omega_m i_{s_d} \quad (21)$$

$$v_{m_q}^* = e_{g_q}^* + R_f i_q + L_f \omega_m i_{s_q} \quad (22)$$

R_f, L_f are known transformer parameters.

By neglecting the PWM/measurement delays and replacing (21-22) in (1-2), respectively, the AC voltage e_g will be equal to its voltage reference in steady-state:

$$e_{g_{dq}} \approx e_{g_{dq}}^* \quad (23)$$

The result in (23) is achievable assuming a good estimation of the filter parameters (R_f, L_f). If the estimation is not accurate, the resulting slight voltage deviation will be compensated by the reactive power control or the secondary voltage control not presented in this work.

To avoid particular resonance linked to the LCL filter, an active damping control has to be implemented:

$$v_{m_d}^* = e_{g_d}^* + R_f i_d - L_f \omega_m i_{s_d} - R_{LCLD} (i_{s_d} - i_{g_d}) \quad (24)$$

$$v_{m_q}^* = e_{g_q}^* + R_f i_q + L_f \omega_m i_{s_q} - R_{LCLD} (i_{s_q} - i_{g_q}) \quad (25)$$

The active damping control in (24) and (25) acts as a physical resistor in series with the filter capacitor C_f (Fig. 3). The active damping may induce a considerable AC voltage drop with respect to the amount of the exchanged power. Therefore, a high-pass filter is implemented so that the damping resistor only reacts to transients.

$$v_{m_d}^* = e_{g_d}^* + R_f i_d - L_f \omega_m i_{s_d} - \frac{R_{LCLD} s}{\omega_R + s} (i_{s_d} - i_{g_d}) \quad (26)$$

$$v_{m_q}^* = e_{g_q}^* + R_f i_q + L_f \omega_m i_{s_q} - \frac{R_{LCLD} s}{\omega_R + s} (i_{s_q} - i_{g_q}) \quad (27)$$

The inner control structure derived from (26-27) is depicted in Fig. 4.

Fig. 3: Emulation of the LCL damping resistor

Fig. 4: Direct AC voltage control scheme

TABLE I: System and control parameters

P_n	1000 MW	f_n	50 Hz
$\cos \phi$	0.95	U_e	320 kV
SCR	10	$e_{g_{dq}}^*$	1 p.u
L_c	0.15 p.u	$e_{g_{dq}}^*$	0
R_c	0.005 p.u	ω_f	60 rad/s
C_f	0.066 p.u	k_p	0.015 p.u
R_v	0.09 p.u	L_f	0.15 p.u
R_f	0.005 p.u	H	5s
n_q	0	R	5%
u_{dc}	640 kV	I_{max}	1.2 p.u
I_n	1 p.u	$\sigma_{X/R}$	5
k_{pRVI}	0.67		

B. Tuning and Small-Signal Stability Analysis of The System Based on The Direct AC voltage Control

In order to assess the system stability and dynamics with respect to the control parameters, the model of the grid-forming inverter depicted in Fig. 1 is linearized around an operating point ($P_0 = 1$ p.u):

$$\begin{cases} \Delta \dot{\mathbf{x}} = \mathbf{A} \Delta \mathbf{x} + \mathbf{B} \Delta \mathbf{u} \\ \Delta \mathbf{y} = \mathbf{C} \Delta \mathbf{x} + \mathbf{D} \Delta \mathbf{u} \end{cases} \quad (28)$$

with:

$$\mathbf{x} = \begin{bmatrix} e_{g_d} & e_{g_q} & i_{s_d} & i_{s_q} & i_{g_d} & i_{g_q} & \delta \omega_m & \delta m \dots \end{bmatrix}^T$$

$$\mathbf{u} = [E_g^* \quad V_e \quad P^*]^T$$

- $e_{g_{dq}}, i_{g_{dq}}, i_{s_{dq}}$ are the LCL filter state variables.
- $\delta \omega_m, \delta m$ are the active power controller state variables.
- δe_g is the reactive power filter state variable.
- $\zeta_{TVR_d}, \zeta_{TVR_q}$ are the state variables of TVR filters.
- $\zeta_{LCLD_d}, \zeta_{LCLD_q}$ are the LCL active damping control state variables.

System and control parameters are presented in Table I. To check the impact of the active damping control on the poles location, R_{LCLD} is varied from 0 to 1 p.u for two values of ω_R as shown in Fig. 5. One can notice from the eigenvalues evolution ($\lambda_{1-2}, \lambda_{3-4}$) that without additional transient active damping, the system will be unstable. The parameter $R_{LCLD} > 0.1$ p.u enhances the stability and damps the oscillatory modes. The parameter ω_R do not have any noticeable impact on stability, however, from an experimental point of view, the choice of a small cut-off frequency allows

avoiding the amplification of the measurements noise. Thus, ω_R and R_{LCLD} are set in the following to 10 rad/s and 0.7 p.u, respectively. The chosen value of R_{LCLD} is sufficient to guarantee a frequency decoupling between the inner and outer loops. This statement is confirmed in the subsection III.C. Based on the chosen parameters, the system eigenvalues are listed in Table II. To illustrate the dynamic behavior of the system based on the proposed strategy, an active power setpoint change of $P^* = 1$ p.u is applied to the system at $t = 1$ s. The simulation results are gathered in Fig. 6. They prove the stability of the system and the ability of the direct AC voltage control to ensure AC voltage tracking in steady state after disturbance.

Fig. 5: Poles Location with respect to R_{LCLD} and ω_R

TABLE II: System Eigenvalues

λ_{1-2}	$-686.4 \pm 3735.4i$	λ_{8-9}	$-60.9 \pm 5.47i$
λ_{3-4}	$-766.4 \pm 3346i$	λ_{10-11}	$-5.17 \pm 6.19i$
λ_{5-6}	$-32.31 \pm 233.65i$	λ_{12-13}	$-9.97 \pm 0.46i$
λ_7	$-31.42 \pm 0i$

Fig. 6: System dynamics in response to the active power change

C. Order Model reduction and control layers decoupling

In large power system, model reduction is of a high interest. It is used to ease the analysis system and to reduce the time computations. The Phasor approximation is one of the model order reduction methods often used for power system analysis. It consists of discarding the fastest dynamics of some state variables x_i by freezing their derivative $\dot{x}_i=0$ and maintaining the slowest ones that define the dominant response of the system. This method is valid provided that the discarded states do not impact the dominant response of the system.

This section aims to demonstrate the decoupling between different system and control modes. A first step consists in finding the link between the fastest eigenvalues λ_i in Table II and the state variables x_i . The aim is to define clearly the state variables to discard and those to keep. The link between eigenvalues λ_i the state variables x_i is usually given by the participation factors. The participation of the state variables x_i in each eigenvalue λ_i is summarized in Table III. In Table III, the eigenvalues are ranked from the fastest to the slowest ones. One can notice that the state variables $e_{gdq}, i_{gdq}, i_{sdq}, \zeta_{TVR_{dq}}, \zeta_{LCLD_{dq}}$ and δe_g are participating in the fastest eigenvalues $\lambda_{1-2}, \lambda_{3-4}, \lambda_{5-6}, \lambda_{8-9}, \lambda_7$ and λ_{12-13} . Therefore, in the case they are neglected, they do not impact the dominant modes λ_{10-11} linked to the active power dynamics δ_m and $\delta\omega_m$. By doing so, the system order can be reduced from 13th to 2nd order (Phasor model), where only the active power dynamics are preserved. To show the system behavior with different levels of reduction, two test cases are performed:

- Active power setpoint change of $P^* = 1$ p.u.
- Grid voltage phase jump of -10 deg.

The results are gathered in Fig.7. Fig.7.a shows that the discarded modes at each stage (13th, 7th, 2nd) do not impact the location of the dominant modes (e.g., 7th order neglecting the grid currents, the inverter currents and the inverter output capacitor, the 2nd order keeping only the active power controller states). This result is also highlighted in Fig.7.b and Fig.7.c through time-domain simulations, where the active power response is nearly the same for both test cases. Based on this study, it is concluded that the inner loops based on the direct voltage control do not interact with the outer power control loop, and thereby, the system dynamics in the case of active power change and phase jump can be simply studied using the simplified linear quasi-static model in Fig. 8. To consolidate the contribution of the direct control structure compared to the conventional cascaded structure. Simulation results from [16] are recalled in this paper in Fig. 9. It shows a wide difference between the Phasor and EMT models.

TABLE III: Participation Factors

Eigenvalues λ_i	Participating state variables x_i
λ_{1-2}	$e_{gdq}, i_{gdq}, i_{sdq}$
λ_{3-4}	$e_{gdq}, i_{gdq}, i_{sdq}$
λ_{8-9}	$\zeta_{TVR_{dq}}$
λ_{5-6}	i_{gdq}, i_{sdq}
λ_7	δe_g
λ_{12-13}	$\zeta_{LCLD_{dq}}$
λ_{10-11}	$\delta_m, \delta\omega_m$

Fig. 7: System performances with order reduction. (a) System modes. (b) Active power change. (c) -10° phase jump

Fig. 8: Phasor model [8]

Fig. 9: Comparison between EMT-based model with a cascaded controller structure and the Phasor model following an active power change [16]

Fig. 10: 10-bus grid case

D. 10-bus grid case study

In this subsection, the grid-forming converter depicted by **HVDC-1** in Fig. 10 is connected to a more realistic grid

configuration instead of a perfect voltage source. The latter consists of two **Wind Parks** (33kV and 66kV) interfaced to the 400kV power system through grid-following based-inverters and two step-up transformers, 1 GVA **HVDC-2** grid-following-based inverter and an equivalent 33 GVA AC grid driven by an equivalent model of synchronous generator [5]. In order to excite the system modes and especially those of the grid-forming inverter, two extreme test cases are applied for the system: 1) a tripping of the corridor between bus A and bus C. 2) 250ms bolted-fault at the bus B. The results are given in Fig. 11 and Fig. 12, respectively, where both EMT-Based EMT-P-RV and RMS-based Ramses [26] simulations are compared.

The tripping of the corridor between bus A and C engenders a significant phase jump and a voltage variation due to the amount of active and reactive power transported at this level, which results in 1800 MW active power variation in the transient at bus A and 250MVAR reactive power injection at both A and B buses to support the AC voltage (see Fig. 11). Despite the severity of the event, the system remains stable and the overall behavior of the system simulated by EMT program is quite close to the one simulated by RAMSES-Phasor program. This conclusion is reinforced through the three-phase short-circuit test case illustrated in Fig. 12. This test yields an overcurrent, which is accurately limited by the virtual impedance to 1.2 p.u as required, and once again, the EMT simulations match the Phasor ones.

IV. EXPERIMENTAL VALIDATION

The aim of this section is to validate experimentally the system operation based on the proposed control. The experimental bench is illustrated in Fig. 13. The 2-Level VSC (1) is supplied by an ideal 600V DC voltage source (4) and connected to a high bandwidth AC amplifier (5) through an LCL filter (3). The amplifier is used to emulate the AC system (i.e.; 300V phph) as well as to generate the events discussed in this paper (i.e.; active power change, 100% voltage sag emulating a 3-phase bolted fault and a phase shift). The 2-Level VSC is controlled with a dSPACE dS1005 (2) with a $40\mu s$ time step. The switching frequency of the inverter is $f_{sw}=10\text{kHz}$. System parameters are listed in Table IV.

Fig. 11: 400ms Three phase short circuit

Fig. 12: 400ms Three phase short circuit

Fig. 13: Mockup presentation & Functional scheme

The electrical quantities displayed in the experimentation are respectively the grid voltages v_g , the grid current i_g (plotted in the oscilloscope), the active power p_{ac} and the inverter output voltage e_g (plotted in dSPACE). Two test cases are performed: a 0.4 active power change and 100% grid voltage sag.

TABLE IV: System Parameters

S_n	5.62 kVA	I_n	10 A
L_f	10.9 mH	L_c	10.9 mH
f_n	50 Hz	C_f	9.2 μ f

A. Active power setpoint change

The power reference is first set to $P^* = 0.1$ p.u. At $t = 3.95$ s, $\Delta P^* = 0.4$ p.u active power change is applied as illustrated in Fig. 14. One can first notice that the system is stable. Additionally, the AC voltage drop resulted from the active power change is compensated thanks to the inverted impedance (L_f, R_f), which yields a negligible AC voltage error in steady state ($\epsilon = 1.6\%$).

B. 100% Voltage sag

Initially, $P^* = 0.5$ p.u. Subsequently, a 400 ms voltage sag is applied as shown in Fig. 15. When the fault occurs, the AC voltage drop induces an increase in the VSC output current, which is limited beyond its maximum allowable current magnitude, 1.2 p.u (12 A). Once the fault is cleared, the system stably recovers its equilibrium point.

V. CONCLUSION

This paper proposes a grid-forming strategy suitable for power transmission system application. It has been highlighted in this paper that the proposed control is very simple and guarantees a well decoupling between different control layers. It has also been demonstrated that the dominant modes of the system associated with the outer power control dynamics are preserved, which allows neglecting the inner dynamics. This satisfies the prerequisite of using Phasor approximation for dynamic studies in large power systems. The feasibility of the proposed control has been proved through experimentation in two faulty cases.

ACKNOWLEDGMENTS

The Authors gratefully acknowledge the contributions of: Thierry Van Cutsem, Bertrand Bastin, Antonin Colot from

Fig. 14: Active Power change

Fig. 15: 400ms Three phase short circuit

University of Liege, Dept. Electrical Engineering and Comp. Sc. Belgium and Dr. Riad Kadri for ENSAM Lille France.

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